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Bethesda, Maryland 20084

THE FABRICATION, PROCESSING AND CHARACTERIZATION OF MULTIDIMENSIONALLY BRAIDED GRAPHITE/EPOXY COMPOSITE MATERIALS

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RESEARCH AND DEVELOPMENT REPORT

October 1984

DTNSRDC/SME-84-66

DTNSRDC/SME-84-66

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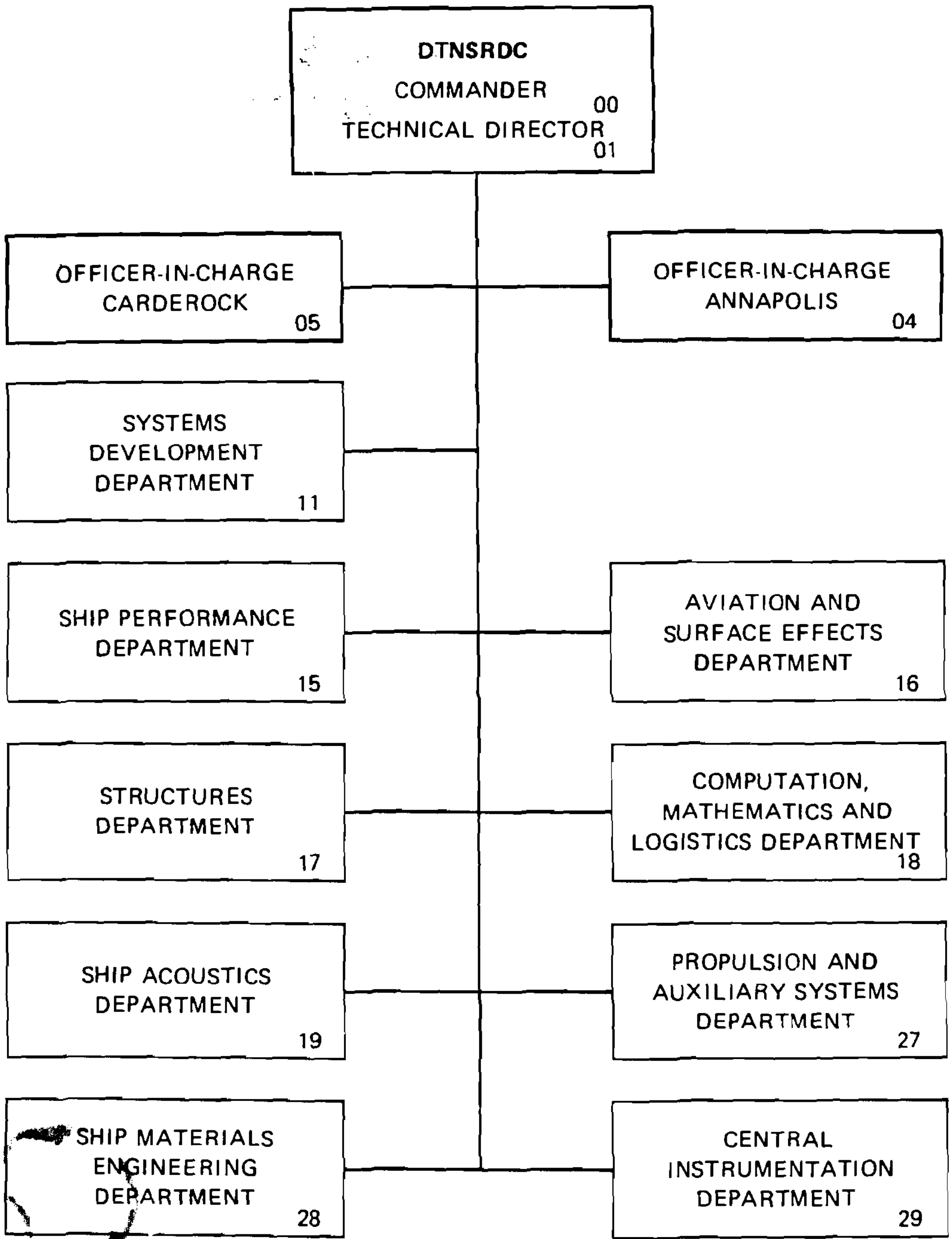

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER DTNSRDC/SME-84-66	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) THE FABRICATION, PROCESSING AND CHARACTERIZATION OF MULTIDIMENSIONALLY BRAIDED GRAPHITE/EPOXY COMPOSITE MATERIALS	5. TYPE OF REPORT & PERIOD COVERED Final Report
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Aleksander B. Macander Roger M. Crane Eugene T. Camponeschi, Jr.	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS David W. Taylor Naval Ship R&D Center Bethesda, MD 20084	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Task SF 61541501 PE 62761N Work Unit 2823-110
11. CONTROLLING OFFICE NAME AND ADDRESS	12. REPORT DATE October 1984
	13. NUMBER OF PAGES 53
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS. (of this report) UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Composites	Resin Impregnation	Drop Ball Impact
Damage Tolerance	Tensile	Ultrasonic C-Scan
Multidimensionally Braided	Compression	Material Properties
Graphite	Flexural	Short-Beam Shear

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes research concerning the braiding, resin impregnation and characterization of multidimensionally braided fiber reinforced composite materials. These materials are an alternative to conventional laminated composite structures and have the potential for being more damage tolerant. The braiding process is initially described, indicating the methodology used and the potential applications for this material.

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S/N 0102-LF-014-6601

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Block 20 continued

Next, three processes are described which have been used for resin impregnation of the multidimensionally braided panels characterized in this study. Two were resin transfer techniques utilizing vacuum or pressure as the transferring machanism while the third was a resin film lamination technique. While all three methods are presented, the latter technique was chosen for impregnating the test specimens due to the consistently low void content and superior surface quality achieved. Three graphite fiber systems were used in this investigation. These were braided into panels in which three braid parameters could be investigated. The variables investigated include the effect of edge condition, braid pattern, and tow size on the tensile, compressive, flexural and interlaminar shear properties. These properties were obtained in the braid direction only. The cutting of the specimen edges substantially reduced both tensile and flexural strengths and modulus. Of the three braid patterns investigated, 1 x 1, 3 x 1, and 1 x 1 x 1/2F, the 3 x 1 braid pattern showed superior tensile performance, while the 1 x 1 x 1/2F braid pattern exhibited superior flexural properties. Fiber tow size variations affect the tensile, flexural and interlaminar shear properties. The 12K tow size resulted in specimens of superior performance compared to the 3K, 6K and 30K tow sizes. All of the uncut edge braided specimens exhibited interlaminar shear strength equal to or greater than unidirectional laminated composites. This characteristic is an indication of the inherent damage tolerance of these multidimensionally braided composites. To further validate this damage tolerant aspect, multidimensionally braided and conventionally laminated panels were impacted and the resulting damage was non-destructively determined. The multidimensionally braided material was shown to substantially reduce the area of damage caused by impact.

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LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
^{o}C	Degrees Celsius
cm	Centimeters
E_{xc}	Compressive Modulus in x-direction
E_{xf}	Flexural Modulus in x-direction
E_{xt}	Tensile Modulus in x-direction
^{o}F	Degrees Fahrenheit
GPa	Giga Pascals
gr/cm^3	grams per cubic centimeters
Hg	Mercury
in	inches
J	Joules
k	Thousand
kPa	Kilo Pascals
ksi	Thousand pounds per square inch
mm	Millimeters
MPa	Million Pascals
Msi	Million Pounds per square inch
psi	Pounds per square inch
σ_{xc}	Compressive strength in x-direction
σ_{xf}	Flexural strength in x-direction
σ_{xt}	Tensile strength in x-direction
V_f	Fiber volume fraction
X-D	Multidimensional

ABSTRACT

This report describes research concerning the braiding, resin impregnation, and characterization of multidimensionally braided fiber reinforced composite materials. These materials are an alternative to conventional laminated composite structures and have the potential for being more damage tolerant. The braiding process is initially described, indicating the methodology used and the potential applications for this material. Next, three processes are described which have been used for resin impregnation of the multidimensionally braided panels characterized in this study. Two were resin transfer techniques utilizing vacuum or pressure as the transferring mechanism while the third was a resin film lamination technique. While all three methods are presented, the latter technique was chosen for impregnating the test specimens due to the consistently low void content and superior surface quality achieved. Three graphite fiber systems were used in this investigation. These were braided into panels in which three braid parameters could be investigated. The variables investigated include the effect of edge condition, braid pattern, and tow size on the tensile, compressive, flexural and interlaminar shear properties. These properties were obtained in the braid direction only. The cutting of the specimen edges substantially reduced both tensile and flexural strengths and modulus. Of the three braid patterns investigated,

1 x 1, 3 x 1, and 1 x 1 x 1/2F, the 3 x 1 braid pattern showed superior tensile performance, while the 1 x 1 x 1/2F braid pattern exhibited superior flexural properties. Fiber tow size variations affect the tensile, flexural and interlaminar shear properties. The 12K tow size resulted in specimens of superior performance compared to the 3K, 6K and 30K tow sizes. All of the uncut edge braided specimens exhibited interlaminar shear strength equal to or greater than unidirectional laminated composites. This characteristic is an indication of the inherent damage tolerance of these multidimensionally braided composites. To further validate this damage tolerant aspect, multi-dimensionally braided and conventionally laminated panels were impacted and the resulting damage was non-destructively determined. The multidimensionally braided material was shown to substantially reduce the area of damage caused by impact.

ADMINISTRATIVE INFORMATION

The work described herein was sponsored by the Naval Sea Systems Command Code 05R25, Dr. H.H. Vanderveldt. This effort was performed at this Center under Task SF 61541501, Element No. 62761N Work Unit 2823-110.

INTRODUCTION

A class of fiber reinforced composite materials is being developed that promises significant improvement in damage tolerance over that possible with conventional laminates. The principal feature of this material is the through-the-thickness network of reinforcing fibers which together with a rigidizing resin form a multidimensionally (X-D)* braided composite. The absence of planes of delamination in this composite results in a tough, crack growth resistant material. Another attractive feature of this new composite material is producibility. It has been demonstrated that the X-D braiding process has the capability to generate both symmetrical and asymmetrical skeletal net shapes of varying thickness and contour which when rigidized with resin become usable structural elements. The technical versatility and the potential for low cost which could be feasible with this process needs to be exploited through extensive research and validation.

This report addresses three aspects which are necessary for an overall investigation of X-D composite materials. These are the requirements of impregnating and rigidizing the X-D skeletal preforms to make them usable structurally, developing a mechanical property data base on the rigidized X-D composite panels, and validating the damage tolerance characteristics of this material.

This report will present a description of the braiding process and the development of a methodology to impregnate and rigidize the X-D skeletal preforms with Narmco's 5208 structural epoxy resin. The importance of the impregnation step cannot be understated as it is a controlling factor that guarantees the quality and desired fiber volume fraction of the finished product. The X-D braided preforms were braided into flat panels using either Thornel T-300,

*Definitions of abbreviations are given on page v.

Celion or AS-4 graphite fibers. These preforms were braided using different tow sizes, braid patterns and edge conditions. The tensile, compressive, flexural and interlaminar shear properties are discussed as a function of the various construction variables. These properties were developed in the braid or axial direction only. An examination of the resulting failure surfaces is also presented. Some comparison of strength and stiffness to conventional laminated composites will be made, with special emphasis given to the improved damage tolerance of the X-D braided construction as demonstrated by the interlaminar shear behavior. In addition, the damage tolerance of X-D composites is investigated by examining the damage resulting from impact testing and comparing the resulting damage to that resulting from impact testing of representative conventional laminated composites.

MULTIDIMENSIONAL (X-D) BRAIDING TECHNOLOGY

The through-the-thickness braiding technique known as multidimensional (X-D) braiding is an extension of the conventional braiding processes. The unique feature of X-D braiding is that fiber preforms can be braided to any thickness whereas conventionally braided preforms are limited in thickness to the dimension of two fiber tows. The development of X-D braiding for fiber reinforced structural applications began in the 1960's at the General Electric Company. General Electric termed the X-D braiding process "Omniweave" and investigated the process for its potential use in the heat shields for tactical missile applications. As the Air Force reduced its emphasis on improving the performance of heat shielding material for tactical missiles, the development of the Omniweave process at General Electric was similarly reduced. A U.S. patent describing ways to increase the speed and versatility of bias weaving and braiding was obtained in 1969 by R. Bluck.[1*]

*References are listed on page 45.

Recently, there has been renewed interest in this process for providing a method to enhance the damage tolerance of advanced composite materials, and in 1982 a patent was issued to R. Florentine on the automation of this braiding process.[2] With the increased use of advanced composites in various structural applications, the risk of foreign object impact damage to composite material has surfaced as a critical problem.[3] The impact damage in laminated structures manifests itself predominantly in the form of delaminations and fiber failures. The delaminations occur due to the resin dominated laminar interface which is weaker than each fiber reinforced laminae. The X-D material has no distinct planes of fiber reinforcement, which should reduce or eliminate the delamination problem, thereby being a damage tolerant alternative to the conventional laminated structure. This critical nature of the improved damage tolerance offered by the X-D material was not exploited for other applications subsequent to the 1960's developments. The X-D braiding methodology these two patents have attempted to automate have been best described by Florentine[4] and Ko[5].

The X-D braided preforms used in this investigation were braided by both the Atlantic Research Corp., Alexandria, Va., and the Philadelphia College of Textiles and Science. A cartesian type loom was used to fabricate both sets of preforms. It should be noted that the X-D braiding methodology, although very attractive and potentially very economical and versatile, at this time is only semi-automatic and highly labor intensive. A fully automatic, computerized system control needs to be developed if the potential of this material is to be realized.

The manual loom used to braid the preforms consists of a rectangular, square or circular base plate; carrier tracks; fiber carriers and an upper header plate. The loom, having a rectangular base plate, is illustrated in Figure 1. Although

it is not obvious from the illustration, the base plate contains grooves into which a number of carrier tracks are inserted. Each carrier track has a regular series of slots along its own length. A cartesian array of slots is formed when the individual tracks with their slots are positioned adjacent to each other. The slots are filled with fiber or yarn carriers to which one end of a yarn is attached while the other yarn end is attached to the header plate. By moving the yarn carriers according to a prescribed regular pattern, the individual yarns move past and around each other in the flat bed of the loom. This is illustrated in Figure 2 which shows a travel pattern of only one individual yarn carrier. Each completed set of motions by all yarn carriers is followed by combing the resulting braid against the header plate. It should be noted that for any motion to occur in the X-Y plane of the loom bed, unoccupied spaces have to exist at the end of each column and rows of carriers. As the braiding proceeds and the yarn elements move across the bed of the loom, the desired preform begins to take a physical shape which corresponds to the shape of the loom bed. This shape can be as simple as a square or be more complicated such as the I-beam section illustrated in Figure 3. It is therefore apparent that the array of yarn carriers located in the plane of the bed is a cross-sectional projection of the part being braided. The successful production of I-beam preforms demonstrated the flexibility of the X-D braiding technique to create a variety of shapes to net contour.

The preform shape used in this investigation had a rectangular section (flat panels). The braid geometries investigated were: 1 x 1, 1 x 1 x 1/2F (50% yarns fixed axially) and 3 x 1. The first number in the braid pattern represents the number of spaces the yarn carrier advanced in the x-direction as a result of the movement in the x direction. The second number represents subsequent spaces the yarn carrier advanced in the y-direction by moving the

the carrier in the y-direction. The resultant orientation of the yarn projected into the x-y plane is thus the vector generated by the x-y motion of the yarn carrier in the bed of the loom. Figure 4 illustrates the serpentine travel pattern of one yarn through a prismatic element, showing that in fact the yarn surfaces on all faces as it travels through the thickness and width of the structure.

RESIN IMPREGNATION OF PREFORMS

The skeletal yarn preform which is braided to net shape must be impregnated with a suitable resin and rigidized. Three impregnation procedures were investigated. These included vacuum impregnation, pressure impregnation and a resin film lamination technique.

The vacuum and pressure impregnation techniques are very similar. In both cases the material to be impregnated is placed in a closed mold having a predetermined internal volume which controls the fiber and resin volume fractions of the finished part. The part thickness can be accurately obtained by using spacers such as 181 style glass cloth, and TX-1040 peel ply material. An example of this set up is shown in Figure 5. The mold is designed to have both resin fill and bleed lines that indicate complete impregnation of the skeletal fiber preform. The mold with the preform and spacers in place is then heated to 121°C (250°F). The resin is also heated in a container to reduce its viscosity. In the vacuum method, the mold is placed into an autoclave or vacuum oven which is evacuated to 762 mm (30 inches) Hg and is preheated to 121°C (250°F). The container of fluid resin outside of the autoclave is connected to the input side of the mold with 6.4 mm (1/4 inch) copper tubing. A valve is located in the system to control resin flow. After all temperatures have stabilized, the valve is opened to allow resin to flow into the mold. The resin is drawn into the mold until there is a steady

flow from the resin bleed lines. The vacuum is then released and the recommended time/temperature cure cycle followed. With the pressure impregnation process, the same procedure is followed with the exception of the transfer of resin. Here, the resin is pumped into an evacuated mold using 690 kPa (100 psi) air pressure. The resin is continuously pumped until a steady flow occurs out the resin bleed lines. Finally, vacuum and pressure are released and the recommended time/temperature cycle is then followed.

It was found that although both methods were promising, quality in terms of controlling voids and porosity was not reproducible. With additional investigation a new method also using a closed mold was developed[6]. This technique, illustrated in Figure 6, uses 3.2 mm (1/8 inch) thick precast resin sheets to impregnate the preform. The dry preform is essentially sandwiched in the mold between two plies of the precast resin sheets. The mold is then placed in an autoclave which is heated to 121°C (250°F) and evacuated to 762 mm (30 inches) Hg. Air is removed from the preform and the melting resin allowing a more positive wicking action of the resin into the preform. After the preform is saturated and the system is free of any entrapped air, the vacuum is released and the mold is removed from the autoclave. At this point in the process the preform is in a B-staged condition, that is, partially cured. The next step in the process is to place spacer material in the mold cavity to control the final thickness of the preform panel. Finally, to control surface smoothness and parallelness, a pressure plate is placed over the mold and the entire assembly is vacuum bagged. The assembly is then placed in a laminating press or an autoclave and the preform cured using the recommended time/temperature/ pressure cycle. This process produced panels of a consistent fiber and resin volume fraction and a void content of less than 1 percent. The technique should be also applicable to more complex

fiber reinforced skeletons such as I-beams, cylinders, foil shapes and other structural sections.

MATERIAL SYSTEMS INVESTIGATED

All X-D braided preforms were impregnated using the resin film lamination technique previously described due to the quality of the impregnated preform. The resin system used was a Narmco Corp. 5208, 177°C (350°F) epoxy resin. The X-D braid characterization was conducted using three graphite fiber systems: Celion fiber produced by the Celanese Corp.; Thornel T-300 produced by the Union Carbide Co.; and AS-4 fibers produced by the Hercules Corp. The fiber properties are given in Table 1. The tow sizes indicated in this table are the number of filaments that make up each tow of fibers.

The Thornel T-300 X-D preforms were purchased from the Atlantic Research Corp., Alexandria, Virginia. The AS-4 and Celion preforms were obtained from the Philadelphia College of Textiles and Science, Philadelphia, Pennsylvania. Table 2 summarizes pertinent information on these materials.

MECHANICAL CHARACTERIZATION

All X-D composite materials were characterized using ASTM tests for tensile, compression, flexural and short-beam shear properties. Specimens were prepared and tested according to the following ASTM methods.

ASTM D3039-76: Tensile Properties of Oriented Fiber Composites

ASTM D3410-75: Compressive Properties of Oriented Fiber Composites

ASTM D790-71: Flexural Properties of Plastics and Electrical Insulating Materials

ASTM D2344-76: Apparent Interlaminar Shear Strength of Reinforced Plastics by Short-Beam Method

Initial testing for compressive properties using the width given in ASTM D3410-75 resulted in variations in strength of about 50 percent. Specimen

width was varied from 6.4 mm (.25 in.) to 25.4 mm (1.00 inch) in order to determine the optimum dimension. From this testing it was shown that widths of 19 mm (.75 in.) and 25.4 mm (1.00 inch) resulted in consistent strengths. These are the widths that were used in subsequent testing.

Three braid parameters were investigated. The first was braid pattern. Three braid patterns were considered: 1 x 1; 3 x 1 and 1 x 1 x 1/2 F. These were braided with Thornel T-300, 30 K tow fibers and were impregnated with Narmco's 5208 epoxy resin. Specimens of each braid pattern were fabricated to widths of 2.5 cm (1 in.) and to widths of 15.2 cm (6 in.) for the 1 x 1, 7.6 cm (3 in.) for the 3 x 1, and 6.4 cm (2.5 in.) for the 1 x 1 x 1/2 F. These wide panels were cut to widths of 2.5 cm (1 in.) following impregnation. This resulted in specimens having edges which were cut and therefore resulted in fiber tows which were discontinuous along the length of the test specimens. This cut edge condition is plausible in the fabrication of various structural shapes as is the uncut edge condition where the structure is braided to net shape. Since both conditions may arise in end use, it was decided to investigate the effect of edge condition (cut or uncut) on the mechanical properties as the second braid parameter. The final braid parameter investigated was the effect of fiber tow size on the mechanical properties of the X-D material. Two fiber systems were investigated, Celion and AS-4. Each was braided with 6K and 12K tow fibers, as well as a 3K tow fiber for the AS-4 material only.

TABLE 1 - MECHANICAL PROPERTIES OF THE CELION, AS-4, and THORNEL T-300 GRAPHITE FIBERS

	Fiber Type/Tow Size		
Fiber Property	Celion 6K, 12K	AS-4 3K, 6K, 12K	T-300 30K
Tensile Strength GPa (ksi)	3.24 (470)	3.59 (520)	2.69 (390)
Tensile Modulus GPa (Msi)	234.4 (34.0)	234.4 (34.0)	220.6 (32.0)
Density gr/cm^3	1.77	1.80	1.77
% Elongation determined from failure strain	1.4	1.53	1.2

TABLE 2 - X-D BRAIDED FIBER PREFORMS USED IN MATERIAL EVALUATION

Graphite Fiber	Fiber Mfr.	Tow[1] Size	X-D Braid[2] Pattern	Preform Size, mm
Celion	Celanese Corp.	6K	1 x 1	3.2 x 25.4 x 254
		12K	1 x 1	3.2 x 25.4 x 254
Thornel T-300	Union Carbide Corp.	30K	1 x 1	3.2 x 152.4 x 254, 3.2 x 25.4, 254
			1 x 1 x 1/2F[3]	3.2 x 63.5 x 254, 3.2 x 25.4 x 254
			3 x 1	3.2 x 76.2 x 254 3.2 x 25.4 x 254
AS-4	Hercules Corp.	3K	1 x 1	3.2 x 25.4 x 254
		6K	1 x 1	3.2 x 25.4 x 254
		12K	1 x 1	3.2 x 25.4 x 254

1 Tow size designation of 3K, 6K, 12K and 30K indicates a filament count of 3,000, 6,000, 12,000 and 30,000 in a yarn bundle respectively.
2 All performs were impregnated with Narmco 5208 epoxy resin.
3 One-half of the fiber in the 1 x 1 braid pattern were fixed in the axial direction.

RESULTS AND DISCUSSION

EFFECT OF EDGE CONDITION AND BRAID PATTERN

The results of the braid pattern and edge condition characterization are given in Table 3. A discussion of the tensile, compressive and flexural test results will follow. Each test set will include discussion on both the braid pattern and edge condition results.

TENSILE PROPERTIES

Two general conclusions can be made as a result of the tensile testing. First, tensile strength and modulus are reduced approximately 50 percent from the uncut edge to the cut edge condition. In the cut edge condition, the 1 x 1 x 1/2F specimens exhibited superior tensile properties whereas in the uncut edge condition, the 3 x 1 specimens resulted in the best tensile performance.

The results obtained from the samples with cut edges are not surprising. The 1 x 1 x 1/2F braid pattern had the highest tensile strength and modulus. In this braid construction, since 1/2 of the fibers have been fixed in the longitudinal direction, not participating in the braiding, there are fibers which remain continuous throughout the entire gage section. Fiber angle also will affect tensile properties, with the larger the angle from the loading direction, the lower the respective strength and modulus. Taking this into account, then, the 3 x 1 braid pattern should have tensile properties greater than the 1 x 1 braid pattern, which is indeed the case.

Comparing the properties of these cut edge braided panels to a laminate with a fiber orientation being $\pm\ \theta$ where θ is the apparent fiber angle of the X-D composite results in the following. The 1 x 1 x 1/2F has a strength and modulus which are 36 percent and 64 percent of a $\pm 12°$ laminate, the 3 x 1 panel has strength and modulus which are 33 percent and 59 percent of a $\pm 12°$ laminate, and the 1 x 1 has a strength and modulus which is 32 percent and 51

TABLE 3 - X-D BRAIDED (THORNEL T-300[1]/5208 EPOXY) COMPOSITE PROPERTY DATA: 1x1, 3x1, 1x1x1/2F BRAID PATTERNS WITH UNCUT AND CUT EDGES

	Fiber Type and Braid Pattern					
Property	T-300 1 x 1 (uncut)	T-300 1 x 1 (cut)	T-300 3 x 1 (uncut)	T-300 3 x 1 (cut)	T-300 1 x 1 x 1/2F (uncut)	T-300 1 x 1 x 1/2F (cut)
V_f (%)	68	68	68	68	68	68
σ_{xt} MPa (ksi)	665.6 (96.5)	228.7 (33.2)	970.5 (140.8)	363.7 (52.7)	790.6 (114.7)	475.7 (68.9)
E_{xt} GPa (Msi)	97.8 (14.2)	50.5 (7.3)	126.4 (18.3)	76.4 (11.1)	117.4 (17.0)	82.4 (12.0)
σ_{xc} MPa (ksi)		179.5 (26.0)		226.4 (32.8)		385.4 (55.9)
E_{xc} GPa (Msi)		38.7 (5.6)		56.6 (8.2)		80.8 (11.7)
σ_{xf} MPA (ksi)	813.5 (118.0)	465.2 (67.5)	647.2 (93.9)	508.1 (73.3)	816.0 (118.3)	632.7 (91.8)
E_{xf} GPa (Msi)	77.5 (11.2)	34.1 (4.9)	85.4 (12.4)	54.9 (8.0)	86.4 (12.5)	60.8 (8.8)
ν_{xy}	0.875	1.36	0.566	0.806	0.986	0.667
Apparent Fiber Angle	$\pm$ 20°	$\pm$ 20°	$\pm$ 12°	$\pm$ 12°	$\pm$ 15°	$\pm$ 12°

NOTE: [1] T-300 Graphite Yarn - 30,000 Tow
[2] Tensile and compression specimens were tabbed at grip ends.
[3] First subscript denotes test direction, second subscript denotes type of test: t - tensile, c - compression, f - flexure.

percent of a $\pm 20°$ laminate. The strength values were computed using the Tsai-Wu tensor failure analysis[7], whereas the modulus was theoretically determined using laminated plate theory. The 1 x 1 x 1/2F braid pattern results in different apparent fiber angles than the 1 x 1 braid pattern. The fixed fibers in the 1 x 1 x 1/2F material significantly alter the fiber angle of the braided preform although the braid patterns are the same.

In the panels with uncut edges, the X-D material exhibited tensile properties which could be ranked in order of increasing fiber angle. The 1 x 1 x 1/2F panel showed a significant increase in properties from the 1 x 1. If the increase is normalized with apparent fiber angle, the strengths are both approximately 90 percent of their respective $\pm \theta$ laminate. The modulus of each braid pattern is approximately equal to the modulus of a $\pm \theta$ laminate. This is significant since the X-D composite is designed to be more damage tolerant. The 3 x 1 panel exhibited the best tensile performance in terms of actual values in the uncut edge condition.

The physical appearance of the failure surfaces of the tensile specimens for all braid patterns were very similar regardless of edge condition. A close-up view of a fractured tensile specimen with uncut edges is shown in Figure 7. The failure appears to be a result of fiber breakage with some evidence of fiber pull-out. The failure surface was basically normal to the loading axis with a minimum of splintering.

COMPRESSIVE PROPERTIES

Compressive properties were only generated for specimens with cut edges. The 1 x 1 x 1/2F panels exhibited the best compressive performance. This is primarily the result of the fixed fibers being continuous and uncut in the test section and the apparent angle of the braided fibers being least off-axis from the loading direction. This braid pattern had a compressive modulus and strength that was 98 percent and 95 percent of the respective X-D cut edge

tensile properties. The 3 x 1 braid resulted in the next highest compressive performance followed by the 1 x 1 braid pattern. The compressive properties of the latter two braids are seen to be a function of the braid angle with the more off-axis fiber orientation resulting in the lower compressive performance. A compression specimen failure is shown in Figure 8. It should be noted that these specimens had cut edges, and typically, failure occurred by shear-out of the braided yarn bundles and subsequent fiber buckling.

FLEXURAL PROPERTIES

The flexural strength of all samples with cut edges were higher than their corresponding tensile strength by at least 40 percent. Normally the flexural strength is greater than the tensile or compressive strength of the material of which it is composed[8,9]. This is the result of the maximum stress occurring in the outer fibers only, whereas in tension or compression testing, the entire cross section develops this maximum stress. Since there is a distribution of strengths in the fibers, the probability of failure occurring in the smaller volume of the flexural specimen is less than that of the larger volume found in the tensile or compressive specimens[10]. The specimens with uncut edges showed increases in flexural strength over the respective X-D tensile strength with the exception being the 3 x 1 braid. Here, flexural strength was only 67 percent of the X-D tensile strength. All flexural moduli were lower than their respective tensile moduli. Whitney and coworkers[9] developed a theoretical model for predicting the bending modulus of laminated composite materials. Using this model, the experimental bending modulus of the 1 x 1 x 1/2F, 3 x 1 and 1 x 1 with uncut edges were 72.7 percent, 66.1 percent and 79.2 percent of the theoretical predictions. The experimental flexural modulus of the 1 x 1 x 1/2F, 3 x 1 and 1 x 1 with cut

edges were 47.1 percent, 42.6 percent and 34.9 percent respectively of the theoretically derived modulus, again, following the theory of Whitney and coworkers[9]. Flexural specimens with uncut edges exhibited failure which manifested itself as resin cracks parallel to the surface tows on the tensile face. Figure 9 illustrates this characteristic flexural specimen failure.

It has been shown that differences in properties exist between X-D braided composite specimens with cut and uncut edges. Accordingly, care should be exercised in the interpretation and application of data that is reported. It could be postulated that the edge effect may be less pronounced in larger width panels. In a subsequent section it will be shown that the actual mechanical capabilities of a large areal panel are better represented by the uncut edge 25.4mm (1.0 in.) specimen data.

EFFECT OF TOW SIZE

Another variable that was also investigated which plays a role in influencing material properties is tow size of the yarn reinforcement. Three tow sizes were thus studied, namely 3K, 6K and 12K for the Hercules AS-4 graphite fiber and 6K and 12K for the Celanese Celion graphite fiber. All materials were braided to a 25 mm (1 inch) width in order that tests be conducted on specimens with uncut edges. As previously noted, the authors consider specimens with uncut edges as being more representative of the X-D braided properties of a large structure. Tensile, flexural and shear properties were developed for these three tow sizes and are given in Table 4. A discussion of the results follows.

TABLE 4 - X-D BRAIDED GRAPHITE/EPOXY COMPOSITE PROPERTIES AS A FUNCTION OF TOW SIZE (UNCUT SPECIMENS, 1 INCH WIDE) INCLUDING COMPARATIVE DATA FOR A LAMINATED FABRIC COMPOSITE

	Fiber Type, Tow Size, and Braid Pattern						
Property	AS-4 3K 1 x 1	AS-4 6K 1 x 1	Celion 6K 1 x 1	AS-4 12K 1 x 1	Celion 12K 1 x 1	Thornel 300 30K 1 x 1	Thornel 300 8 Harness Satin Fabric
V_f, %	68	68	56	68	68	68	65
σ_{xt} MPa (psi)	736.8 (106870)	841.4 (122040)	857.7 (124400)	1067.2 (154790)	1219.8 (176910)	665.6 (96530)	517.1 (75000)
E_{xt} GPa (Msi)	83.5 (12.1)	119.3 (17.3)	87.8 (12.7)	114.7 (16.6)	113.1 (16.4)	97.8 (14.2)	73.8 (10.7)
τ_{SBS} MPa (psi)	114.8 (16650)	126.0 (18270)	71.4 (10350)[2]	121.4 (17600)	71.4 (10350)[2]		69.0 (10000)
ν_{xy}	0.945	1.051	0.968	0.980	0.874	0.875	0.045
σ_{xf} MPA (psi)	885.3 (128400)	739.8 (107300)		1063.3 (154210)		813.5 (117990)	689.5 (100000)
E_{xf} GPa (Msi)	84.5 (12.3)	95.2 (13.8)		138.6 (20.1)		77.5 (11.2)	65.5 (9.5)
Apparent Fiber Angle	$\pm$ 19°	$\pm$ 15°	$\pm$ 15°	$\pm$ 13°	$\pm$ 17.5°	$\pm$ 20°	0°

NOTE: [1] Tensile specimens were tabbed with 1.6 mm (1/16 inch) thick 25.4 mm (1 inch) x 63.5 mm (2-1/2 inch) glass reinforced plastic tapered tabs at grip ends.
[2] Celion 6K and 12K specimens had cut edges for the short-beam shear tests only.

TENSILE PROPERTIES

The tensile data from Table 4 are presented graphically in Figure 10. From the bar graph it appears that for the three tow sizes investigated, specimens with the 12K tow reinforcement have the highest ultimate tensile strengths. Tensile strength seems to increase with tow size for both the AS-4 and Celion fibers. Although not part of the initial tow study, tensile strength in Table 4 for the Thornel 300 material having a 30K tow, appears to be comparatively lower than for the other tow sizes. Therefore, considering the differences in the various fibers used, with Thornel 300 having the lowest fiber strength as seen in Table 1, the initial implication that tensile strength was continuously increasing with tow size needs to be modified. It is thus proposed that the performance of the 12K tow specimens may suggest a certain optimum tow size. With the exception of the AS-4, 3K; Celion 6K and Thornel 300 30K specimens it is shown in Table 4 that tensile modulus was consistently on the high side in the range of 110 GPa to 117 GPa (16 to 17 x 10^6 psi). The seemingly anomalous values of modulus for the 3K and 30K specimens may be attributable to the variation in apparent fiber angles. It is appreciated that these differences could have an adverse effect on tensile strength but not to the extent observed. For example the Tsai-Wu Tensor Failure Theory[7] only predicts a 23 percent reduction in strength in an AS-4 laminate when fiber orientation is changed from $\pm$ 15° to $\pm$ 20°. The reduction shown in Table 4 for the 3K AS-4 material is 44 percent for tensile strength and 37 percent for modulus when compared to the 12K material. This large reduction in properties cannot solely be attributed to the greater apparent fiber angle in view of the Tsai-Wu Theory. It is surmised that other variables not clearly identified play a significant role in this reduction.

Another phenomenon that may play a significant role in the performance of X-D braided composites is the axial effect created by the "crowding" of the braid yarns at the specimen edges. Although this effect appears to improve overall composite properties, the extent of the crowding effect may depend on tow size and may be more pronounced as the tow size increases. It is postulated that such is the case for the 12K tow specimens, where this edge effect may extend further into the specimen width than is the case for the 3K tow. As a result, the 12K material has superior properties.

Table 5 presents experimental values of tensile strain to failure in both the longitudinal and transverse directions for both AS-4 and Celion specimens. For the Celion specimens, it is seen that the longitudinal strain to failure is approximately 75 percent of the failure strain of the fiber alone. However, the AS-4 specimen had a longitudinal failure strain approximately 50 percent lower than that of the fiber alone. This would tend to indicate that the AS-4 fiber may have been either mishandled, processed differently from the Celion, or in fact be inherently susceptible to damage. In any case, if the failure strain of the AS-4 material was comparable to Celion, similar tensile performance would have been expected.

FLEXURAL PROPERTIES

The flexural test results developed, using a span to depth ratio of 16:1, are given in Table 4. The significance of the flexural data developed in this investigation may be more meaningful if put in the context of work done by others for laminated composites. Several investigators have shown that in general flexural strength is greater than tensile or compressive strength of the material of which it is made[8,9,10]. Again, this behavior is explained to be a consequence of the nonuniform stress distribution through-the-thickness of

TABLE 5 - STRAIN TO FAILURE OF THE 1 x 1 BRAID AS-4 AND CELION TENSILE SPECIMENS (DATA OBTAINED FROM STRAIN GAGES)

	Longitudinal Strain at Failure (%)	Transverse Strain at Failure (%)	Fiber Elongation at Break (%)
Celion 6K	1.04	1.08	1.4
Celion 12K	1.08	1.03	1.4
AS-4 3K	0.87	0.68	1.53
AS-4 6K	0.76	0.70	1.53
AS-4 12K	0.89	1.08	1.53

NOTE: Celion Data reported in manufacturer's brochure
AS-4 Data reported in manufacturer's brochure

the flexural specimen. In the flexural specimen, the maximum stress occurs only in the outermost fibers and thus the probability of a flaw to be located within this region of higher stress and thus contributing to failure is lower than it would be for the entire specimen. On the other hand, in tensile or compressive specimens, the entire cross-section of the specimen is assumed to experience an average stress. Thus, the probability of a flaw existing in this net section and contributing to failure and reduced strength is greater than for the flexural specimens.

In general, the data given in Table 4 tends to support the findings on flexural strength discussed by Bullock[8], Whitney[9], and Zweben[10]. The 3K specimen showed a flexural strength value which was 20 percent greater than its tensile strength. However, the flexural strength of the 6K specimen was 12 percent lower than its tensile strength. The 12K specimen had a flexural strength equal to its tensile strength.

Zweben[10], gives an extensive review of the flexural test method used in this investigation and cautions that the shorter span specimens recommended by ASTM D760 may actually give reduced flexural modulus values. He indicates that a laminate whose plies are uniformly spaced and oriented and whose tensile and compressive moduli are equal should have a flexural modulus whose value would equal the tensile modulus. Deviations from this may result from several sources. The two which are noted here are resin rich surfaces and improper span-to-depth ratios of test specimens. Zweben recommends a ratio of 60:1 for measuring flexural modulus as this significantly minimizes the deflection contribution due to shear effects.

In this investigation, since a span-to-depth of 16:1 was used, one would expect the flexural modulus to be lower than the tensile modulus. Furthermore,

additional reductions in modulus could also be expected as a result of resin rich specimen surfaces. On examination, no such resin rich surfaces existed. The resulting data from this investigation was found however, to be inconsistent. Table 4 shows that for the 3K material, the value of flexural modulus was equal to the value of the tensile modulus. The 6K flexural modulus was 20 percent less than the tensile modulus, whereas the 12K flexural modulus was 20 percent greater than the tensile modulus. Zweben[10], using a span-to-depth ratio of 16:1, reports a flexural modulus for a unidirectional Kevlar 49/polyester composite which is 35 percent lower than a modulus obtained with a span-to-depth of 60:1. This information has a bearing on the data of Table 4 as it suggests a higher value of flexural modulus for the AS-4 materials if a 60:1 test specimen was used. Zweben shows that as the span-to-depth ratio increases, the flexural modulus assymptotically approaches the tensile modulus. Furthermore, to resolve inconsistencies such as those shown in Table 4, Zweben recommends that a specimen with a 16:1 ratio be used for strength determinations and a specimen with a 60:1 ratio be used for flexural stiffness determinations.

The mode of failure was examined for each of the flexural specimens tested. Specimens of each tow size were sectioned, mounted and polished. Photomicrographs of the failed sections are given in Figure 11. In each specimen, the damage occurred on the compressive side of the specimen in the form of fiber debonds. Due to the nature of the braid pattern, the debonds were not planar and followed a quasi-continuous path, parallel to the surface of the specimens. The number and lengths of the debonds varied from one braid pattern to another.

The 3K flexural specimens showed the greatest number of yarn debonds as shown in Figure 11(a). Debonds appear to originate at the loading face and

continue to propagate, coalescing one plane below the surface normal to the loading nose in both directions. The debonds continue to progress into the thickness of the material, propagating outward from the loading area.

The 6K specimen showed similar damage behavior as illustrated in Figure 11(b). Here again, fiber debonds progress from the compressive surface for a distance of one tow thickness below. At this point, they seem to coalesce to form a pseudo planar delamination. There is an additional debond which occurs one tow thickness below the previous debond. This additional debond seems to initiate from the previous debond at a position where a second tow transitions into the thickness above. The severity of damage in this specimen is less than that contained in the 3K specimen.

The 12K specimen had the least damage as observed in Figure 11(c). Some debonds occurred but appeared to be contained and not allowed to progress to the extent that they did in the 3K and 6K specimens. In this instance, evidence of tow fracture is noticeable. These cracks progress normal to the surface to a depth approximately three tow thicknesses into the specimen.

From this cursory examination, it appears that the larger tow sizes are more capable of inhibiting debond growth than are the smaller tows. This may be the result of two phenomena. First, with the smaller tow, there appears to be more of a discontinuity between the tows caused by larger pockets of resin at the crossover region of the fibers. Second, the angles that the fibers appear to have as they progress through the material may exacerbate the debond propagation. The smaller tows appear to contain larger angular differences than the larger tows in the plane of the material. Also, the braid length may affect the angular transition of fibers in their travel through the specimen. These aspects have not been addressed adequately to obtain a comprehensive explanation of the damage progression.

SHORT-BEAM SHEAR PROPERTIES

The short-beam shear properties which were developed in this investigation are gage marks indicative of the ability of X-D braided materials to resist in-plane shear loads and suppress damage growth. Conventional laminated composites have an inherent weakness which manifests itself in poor resistance to interlaminar shear. For instance this weakness usually results in extensive damage to the composite especially if subjected to low velocity impact. With the X-D braided composite, delamination as such does not exist due to the multidimensional, interconnecting network of fibers. What has been shown in the previous discussion on bending is a shear mode of failure where yarn tows experience debonding.

ASTM method D2344-76 was used to conduct the short-beam shear tests. The specimens had a span-to-depth ratio of 4:1 although the requirement for specimen width was modified to 25.4 mm (1 inch), i.e., the uncut width of the braided composite, rather than the accepted width of 6.4 mm (1/4 inch). The results given in Table 4 show shear values for all AS-4 fiber tow sizes in the range from 110.2 to 124.1 MPa (16 to 18 ksi). By contrast a typical laminated composite using graphite fabric has a short-beam shear of 69 MPa (10 ksi). Thus it is seen that the AS-4 material represents an approximate improvement of 60 to 80 percent over the conventional fabric laminate, and in fact these improvements are equal to or exceed unidirectional interlaminar shear values.

These results are even more promising in light of the 25.4 mm (1 inch) specimen width used. Sattar and Kellogg[11] showed that width plays a factor in the stress distribution of the short-beam specimen, where shear strength varies across the width, being maximum at the edges and a minimum at the center. They showed that the short-beam shear strength, as determined from

beam theory was a conservative estimate of the short-beam shear strength and becomes increasingly more conservative up to a width-to-depth ratio of 4:1. For the 25.4 mm (1 inch) wide specimens used in this investigation, the width-to-depth ratio was approximately 10:1. This choice was due to the fact that an uncut, full width specimen was desired to avoid damage resulting from cut edges. The trend from Sattar & Kellogg's work would indicate that the short-beam shear strength determined in this investigation from beam theory is a conservative estimate.

In order to gain an insight into the fracture sustained by the X-D braided materials, tested short-beam shear specimens were suitably prepared and examined. Failure surfaces for the AS-4 braided 3K, 6K and 12K tow specimens are shown in Figure 12. It was found that all specimens sustained some form of damage on the tensile face. Specifically, the 3K tow specimens exhibited fiber fracture with cracks progressing along and into (normal) the tensile face of a specimen. Yarn debonds were found to exist, but growth appeared limited and did not extend deeper than a few tows into the thickness. Yarn debonds only occurred at tow/resin interfaces. The 6K specimens which carried a higher shear stress, had very few cracks along and into (normal) the surface on the tensile side. However, tow debonds within the body of the specimens appeared to be more numerous than for the 3K specimens. These debonds were not limited to the tow/matrix bond but also occurred within the individual tow. The damaged region was larger and more severe. It would thus appear that the 6K material has a greater capacity for damage tolerance since it was able to develop a much higher failure load than the 3K material (a 26 percent improvement). This would tend to indicate that as the loading progressed, the damage that occurs is self-limiting and the specimen can continue to carry increasing loads up to a critical threshold value. The 12K

tow specimens had a shear value somewhat lower than the 6K tow specimens and exhibited a damage condition very similar to the 3K specimens. Table 4 also gives values for the Celion 6K and 12K tow specimens which had cut edges. The lower shear values for these specimens compared to the AS-4 specimens with uncut edges is also illustrative of the edge effect discussed previously.

EFFECT OF SPECIMEN WIDTH ON TENSILE MODULUS

The previous testing of the T-300 material with the three braid patterns showed that there was a marked difference in tensile properties between the specimens with cut and uncut edges. In the authors opinion, the specimens with uncut edges in the 2.54 cm (1.0 in.) widths would have properties more representative of properties in a large structure than specimens with cut edges. The braid pattern in the uncut edge specimens varies from the edge of the specimen to the center of the specimen. At the edges, the tows become aligned in the loading direction, resulting in apparent fiber angles of 0°. The 30K tows in the processed panel are flattened to a width of approximately 3.2 mm (1/8 in.). In the 2.54 cm (1.0 in.) wide samples, this edge tow orientation can constitute approximately 25 percent of the total width.

To examine the effect of this edge tow orientation on tensile modulus a 7.6 cm (3.0 inch) wide panel was fabricated and tested. The testing procedure followed was that given in the standard ASTM D3039-76. Five strain gages with a grid width of 6.4 mm (0.25 in.) were mounted on the specimen, centered at 1 cm (0.375 in.), 2.4 cm (0.94 in.), 3.8 cm (1.5 in.), 5.2 cm (2.06 in.) and 6.7 cm (2.63 in.) from an edge. The specimen was tested to a stress level of approximately 193 MPa (28 ksi). The results are given in Table 6.

Table 6 shows that a modulus variation does exist across the width of the specimen. The fiber direction at the edges significantly increases the modulus of the material, an increase of approximately 24 percent from the

TABLE 6 - TENSILE MODULUS, E_{XT}., OF A 7.6 cm (3 inch) 3 x 1 BRAIDED PANEL AS FUNCTION OF WIDTH

	Gage Location as Measured Specimen Left Edge				
Property	1 cm (.375 in.)	2.4 cm (.94 in.)	3.8 cm (1.5 in.)	5.2 cm (2.06 in.)	6.7 cm (2.63.in.)
E_{XT}[1] GPa (Msi)	110.9 (16.09)	89.7 (13.01)	89.2 (12.94)	95.7 (13.88)	103.7 (15.04)

[1]E_{XT} - Tensile Modulus in x-direction.

modulus at the specimen center. The modulus values shown here are somewhat lower than the values for the 2.5 cm (1 inch) 3 x 1 braid uncut edge specimens shown in Table 1. One reason for this is due to the lower fiber volume fraction of the 7.6 cm (3 inch) wide sample, approximately 58 percent. To attempt to correct for this, a laminated plate analysis in conjunction with a rule of mixtures estimation of modulus was performed on a $\pm 10°$ laminate with fiber volume fractions of 58 percent and 68 percent. The increase in tensile modulus, E_x, from 58 to 68 percent fiber volume fraction was approximately 19.3 GPa (2.8 Msi). This will be used as an approximate correction for the 7.6 cm (3 inch) wide panel for comparison purposes with the 2.5 cm (1 inch) wide panel. The edges of the 7.6 cm. (3 inch) panel are seen to have a corrected modulus of 124 GPa (18 Msi) and 117.2 GPa (17 Msi) approaching that obtained in the 2.5 cm (1 in.) panel, 126.2 GPa (18.3 Msi). The center of the 7.6 cm (3 in.) panel would have an approximate modulus of 108.9 GPa (15.8 Msi), which is higher than the average of the modulus of cut and uncut 3 x 1 specimens, 101.4 GPa (14.7 Msi). This supports the author's initial hypothesis that the 2.5 cm (1 in.) samples with uncut edges are a better indication of tensile performance than samples with cut edges. This edge effect phenomenon is in need of further investigation.

IMPACT TESTING FOR DAMAGE TOLERANCE DETERMINATION

The X-D braided composite construction has the potential for being more damage tolerant than conventional laminated composites. Laminated composites have an inherent weakness of poor interlaminar shear strength. When the laminated material is impacted, damage occurs by many mechanisms including delamination. The delaminations occur due to the weak interlaminar properties.

The X-D composite material is not made of individual unidirectional laminae. Impact should not, therefore, create planes of delamination and damage resulting from an impact condition, should be contained.

To determine the ability of the X-D braid configuration to contain damage, a 7.6 cm (3 in.) wide 3 x 1 X-D braided panel and three 7.6 cm (3 in.) wide laminated panels were subjected to a drop ball impact test of 27 J (20 ft-lb) of energy.

Figures 13 and 14 show ultrasonic C-scans of both the X-D panel and a $[(10/-10)_6]_s$ laminate respectively. The damage in the X-D panel has been limited to the panel's center as shown by the light area in the C-scan. The edges of the material are undamaged, as shown by the similarity of this region with the control panel. The resultant areal dimension of damage is only 30% of the test section. The laminated composite, on the other hand, has damage which is uncontained. The entire unsupported region has delaminated or experienced some other form of damage. This is seen by comparing the impacted panel with the control panel's C-scan. This shows that the X-D material does inhibit damage growth and is thus more damage tolerant.

SUMMARY

The multidimensionally braided preforms generated for this investigation have been impregnated with a typical structural epoxy resin and cured successfully. Processing problems commonly encountered by other investigators relating to impregnation and air entrapment have been resolved as documented by this report.

The through-the-thickness or multidimensionally braided composite has performance characteristics which are superior to fabric laminated composites in the braid direction only. This is clearly evidenced by improved axial strength, axial stiffness and short-beam shear properties as observed in Tables 3 and 4.

The performance of the braided composite is a function of both tow size and braid pattern. The investigation suggests that an optimum tow size may exist as evidenced by the superior tensile and flexural properties of the 12K tow composite. Likewise, an optimum braid pattern may be present as witnessed by the highest tensile properties obtained with the 3 x 1 braid pattern. Thus, it would not be unreasonable to meld the 12K tow size with the 3 x 1 braid pattern and expect tensile and flexural properties far superior to laminated fabric composites, even approaching properties of unidirectional composite configuration. The investigation also showed that there is a definite edge effect which governs the behavior of all braided composite coupon specimens. Results indicate that specimens with fully braided, i.e., uncut edges, have higher "all around" axial values including interlaminar shear resistance as compared to specimens with cut edges. The data obtained on uncut specimens are more representative of the areal strength and stiffness of full size braided structural elements than are data from cut edge specimens. The uncut edge properties have, however, been shown to be unconservative. Impact testing of other investigators, such as Brown[12] and Gause[13], also indicate that X-D braided composites are more damage tolerant than laminated composites. This is further evidenced by the static test results of this study which indicate that failure surfaces are reduced in size since sequential ply failure no longer exists.

The information reported in this paper represents an effort to develop material property data which is currently very limited for multidimensionally braided composites. It should be noted that there remain significant technical areas which require attention. These areas of interest pertain to: (1) Material properties including far more axial data as well as transverse

and through-the-thickness behavior under both static and dynamic conditions; (2) Analytical capability that could relate part geometry, braid orientation and braider operation; (3) Automated fabrication capability to realize full (technical and low cost) potential of the X-D braiding process; (4) Nondestructive evaluation capability; and (5) Repair capability.

CONCLUSIONS

Impregnation of the X-D composite material using the resin film lamination technique is capable of consistently producing flat panels with high fiber content and a void content of less than 1 percent. Of the three X-D braid configurations examined (1x1, 1x1x1/2F and 3x1), the 3x1 construction has demonstrated the best over all performance. The data for the 12K tow braided composite seems to indicate the existence of an optimum tow size. The X-D braided construction has shown its ability for limiting damage progression caused by impact loading. This shows that the X-D braided construction results in material which has increased damage tolerance over conventional laminated composites.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the technical encouragement and financial support of Dr. H. H. Vanderveldt of the Naval Sea Systems Command. They also wish to thank Mr. Robert Blake of the University of Delaware for performing the Ultrasonic C-scans testing used in this investigation.

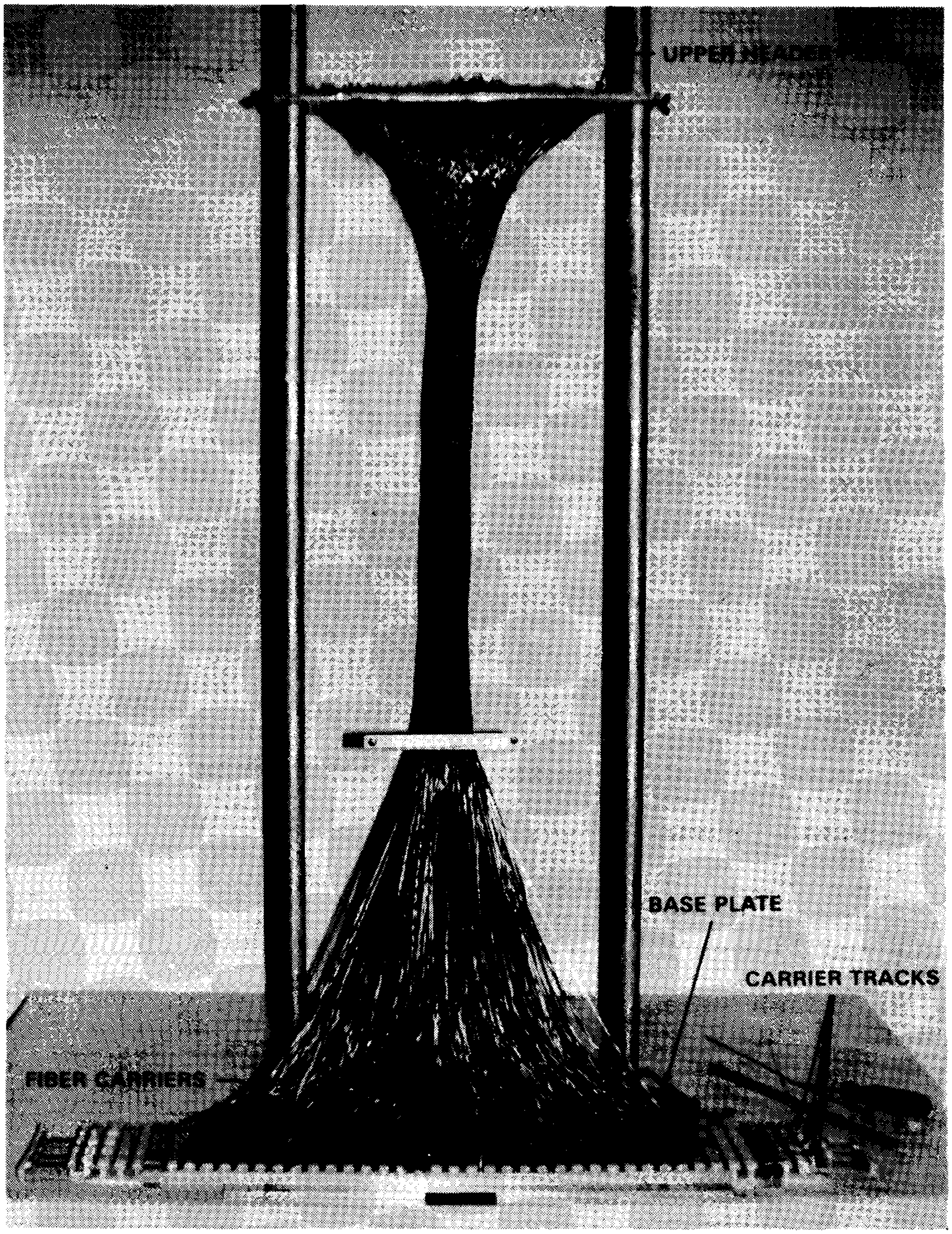


Figure 1 - Manual Loom for Multidimensional Braiding
of Skeletal Yarn Preforms
(Atlantic Research Corp.)

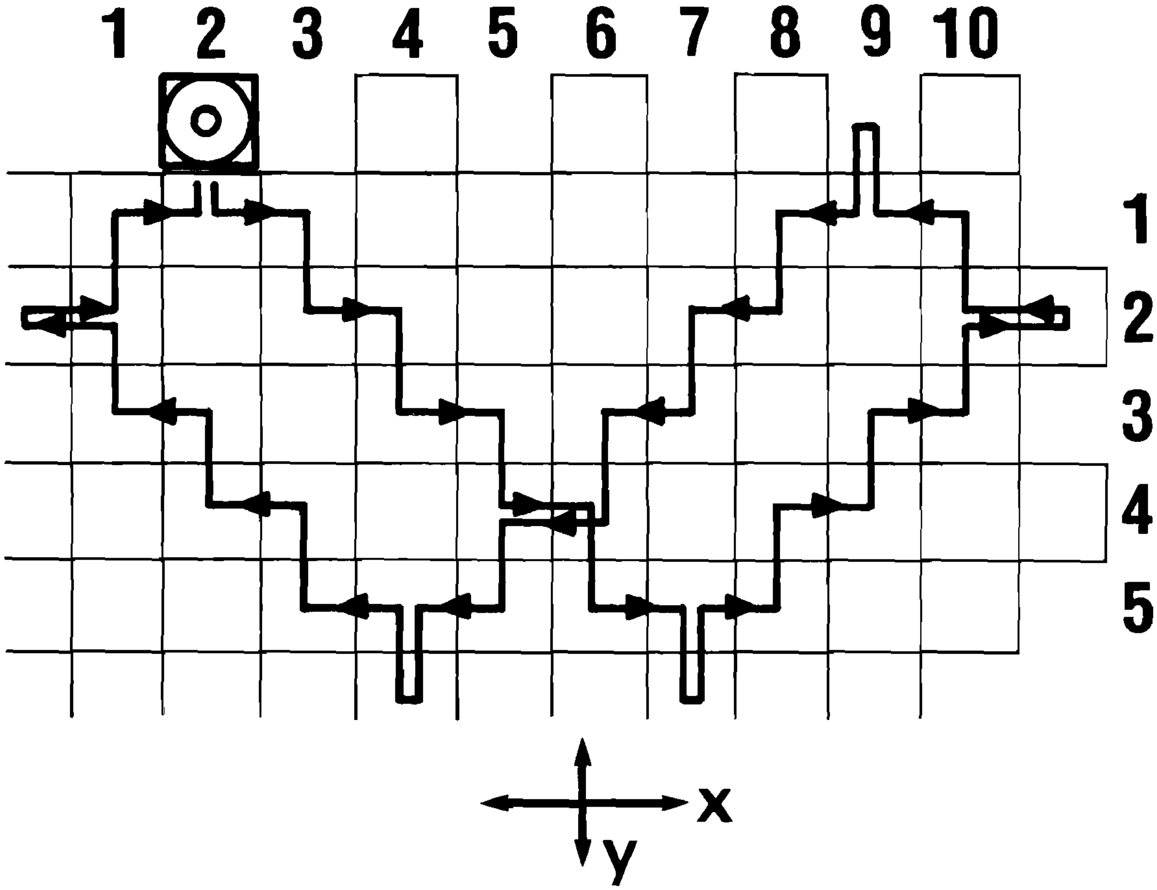


Figure 2 - Schematic of the X-Y Motion of One Year Carrier in the Cartesian Bed of a Loom; Carrier is Following a 1 x 1 Braid Pattern (after Florentine[2])

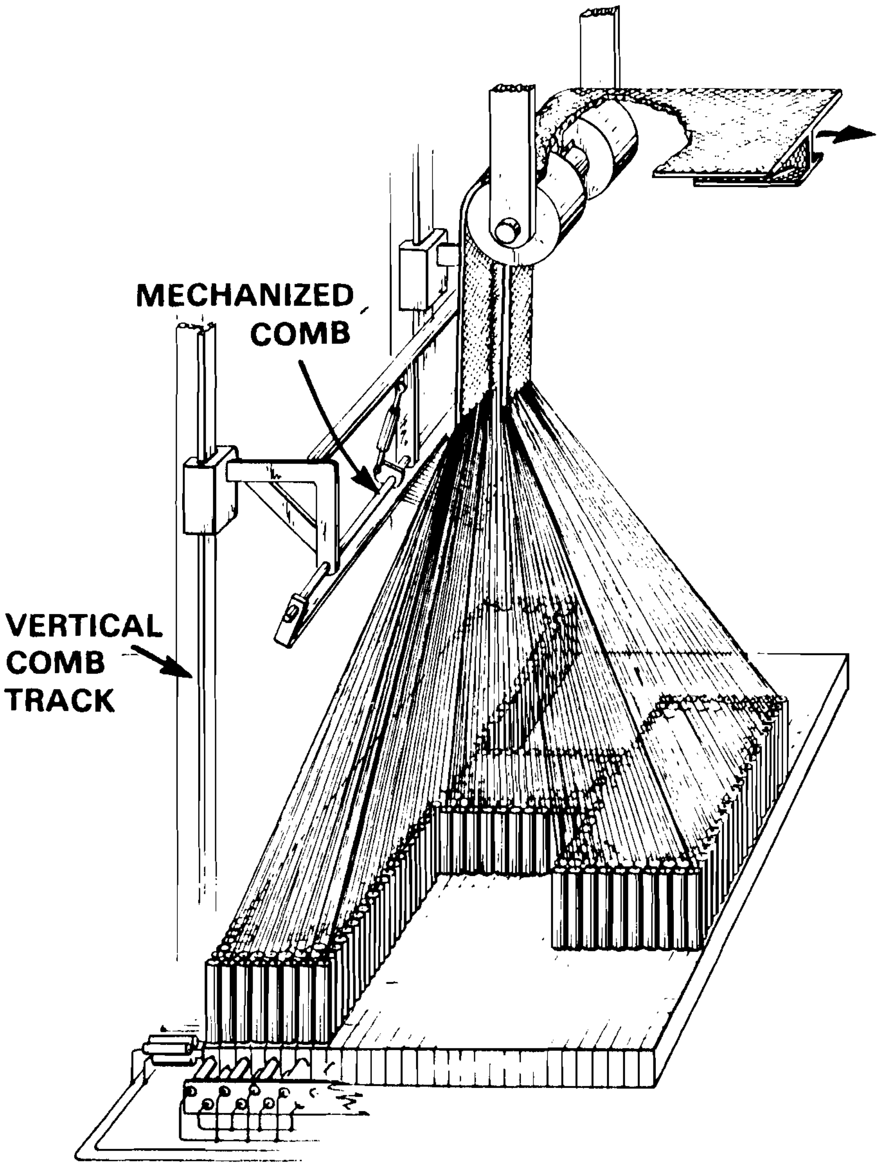


Figure 3 - Schematic of an X-D Braiding Apparatus for Braiding I-Beams (Atlantic Research Corporation)

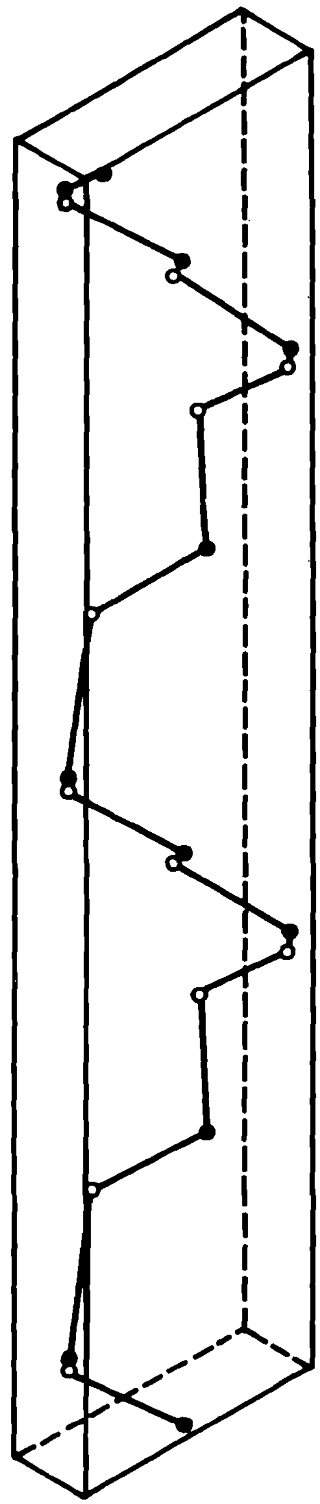


Figure 4 - Travel Path of One Yarn Through a Prismatic Element of a Multidimensionally Braided Material (Atlantic Research Corporation)

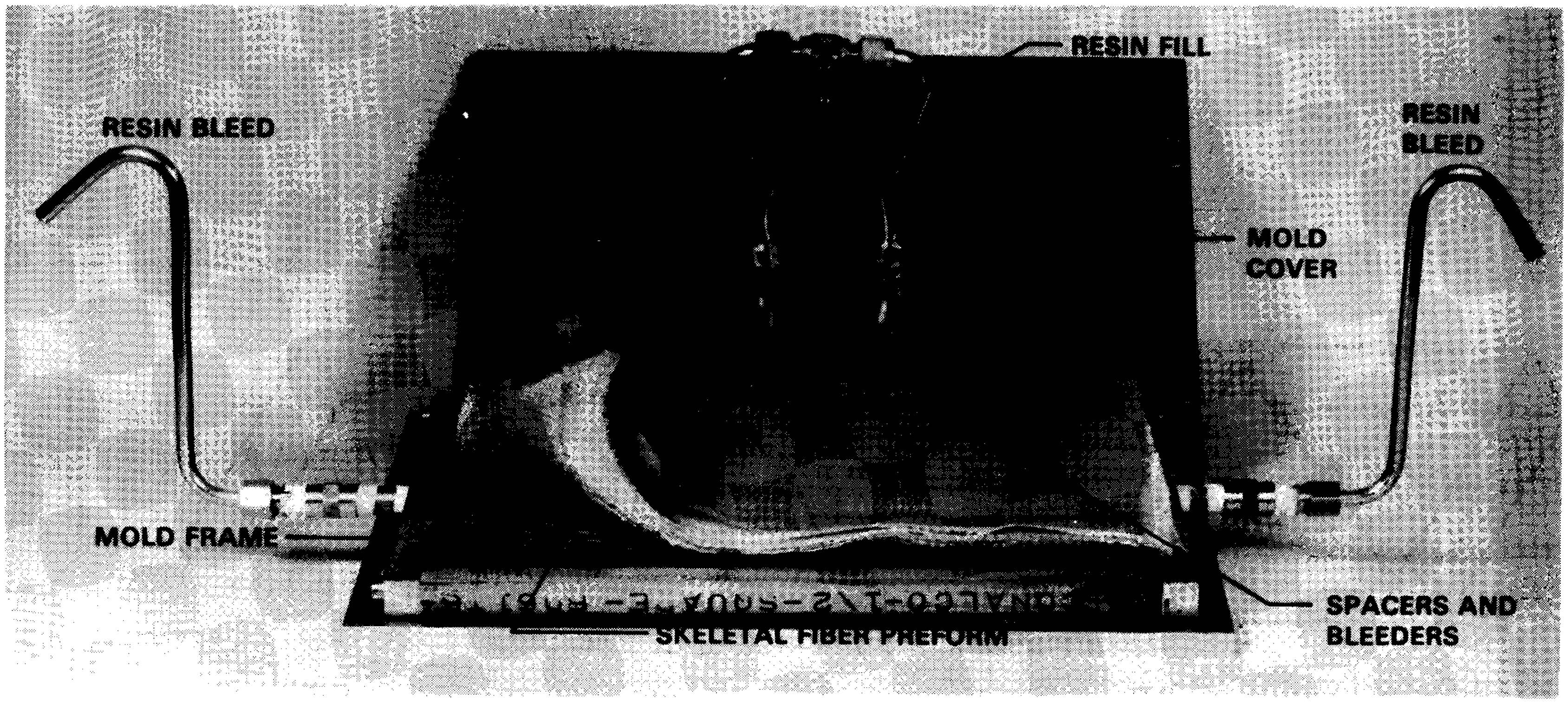


Figure 5 - Vacuum and Pressure Resin Impregnation Techniques for X-D Braided Preforms

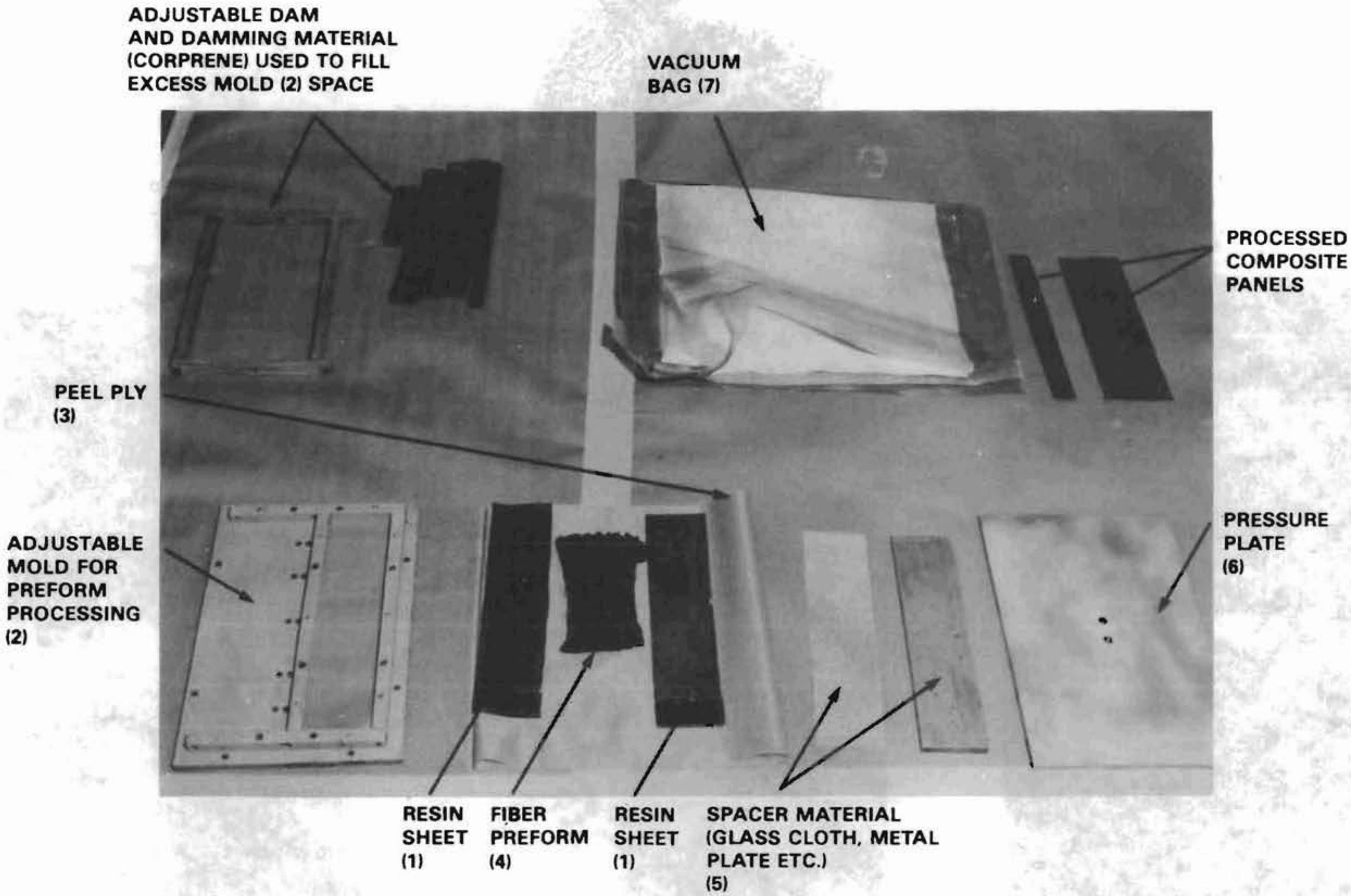


Figure 6 - Resin Impregnation Technique for X-D Braided Preforms Using a Resin Precast Sheet and a Closed Mold Termed the Resin Film Lamination Technique

Figure 7 - Fractured Tensile Specimen, T-300/5208, 30K Tow

Figure 8 - Fractured Compression Specimen, T-300/5208, 30K Tow (View of Cut Edge Showing Tows Debonds)

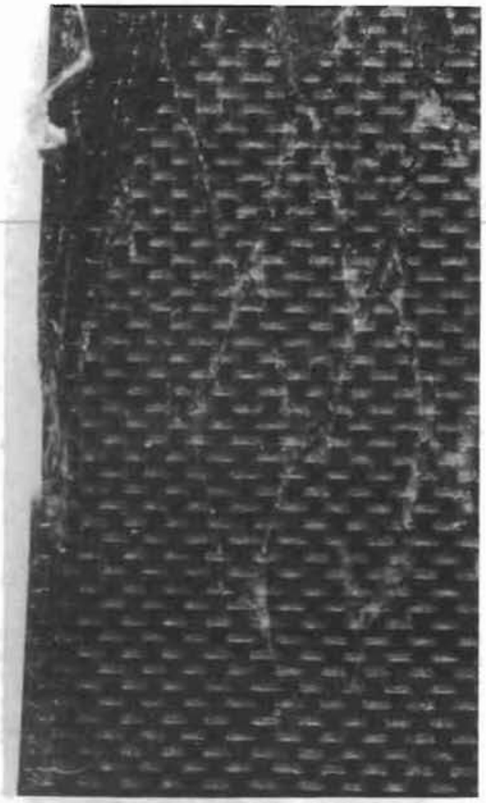


Figure 9 - Fractured Flexural Specimen, T-300/5208, 30K Tow (Surface View Showing Tow Debonds)

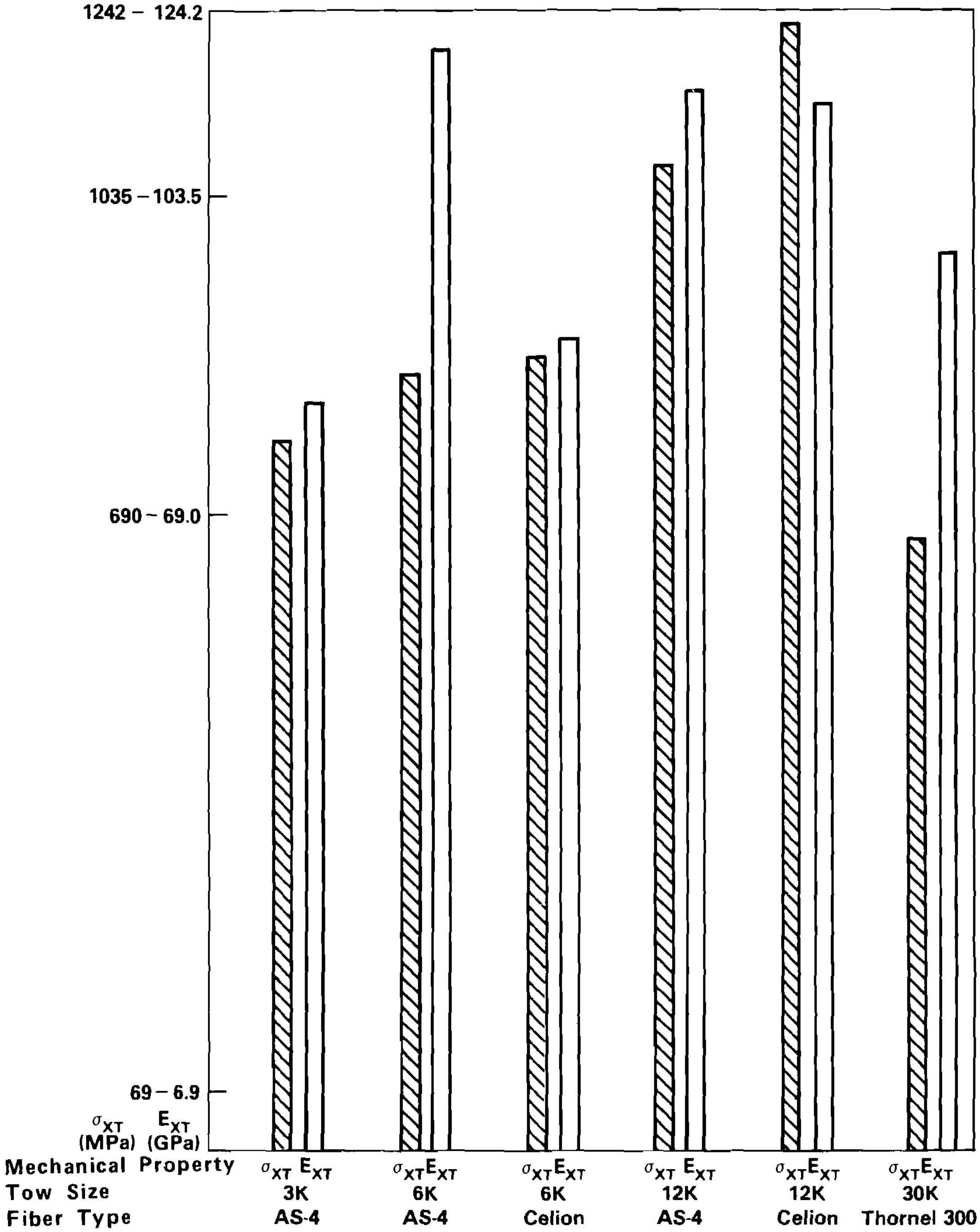
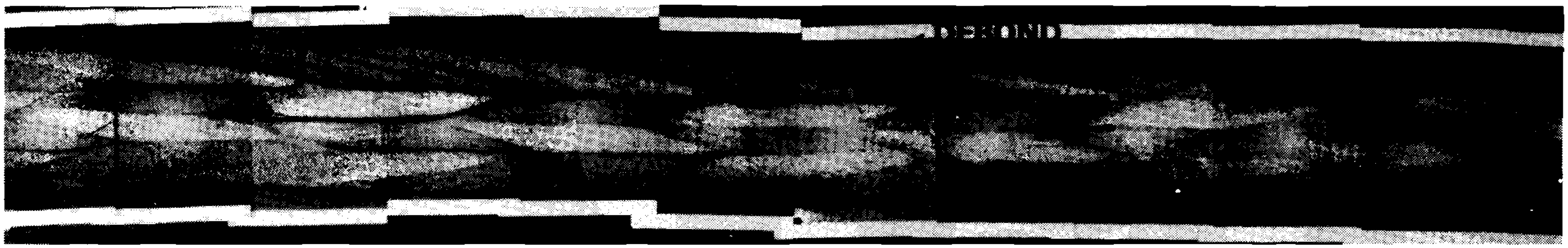


Figure 10 - Graphical Representation of Tensile Strength and Modulus of AS-4, Celion and Thornel 300, 1 X 1 Braided Composites of Various Tow Sizes

(a). 3K TOW

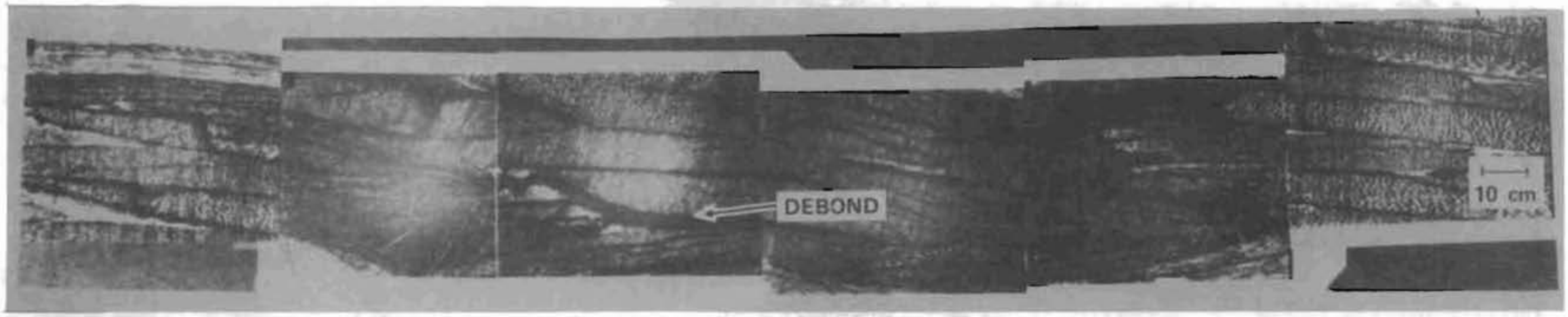


(b). 6K TOW

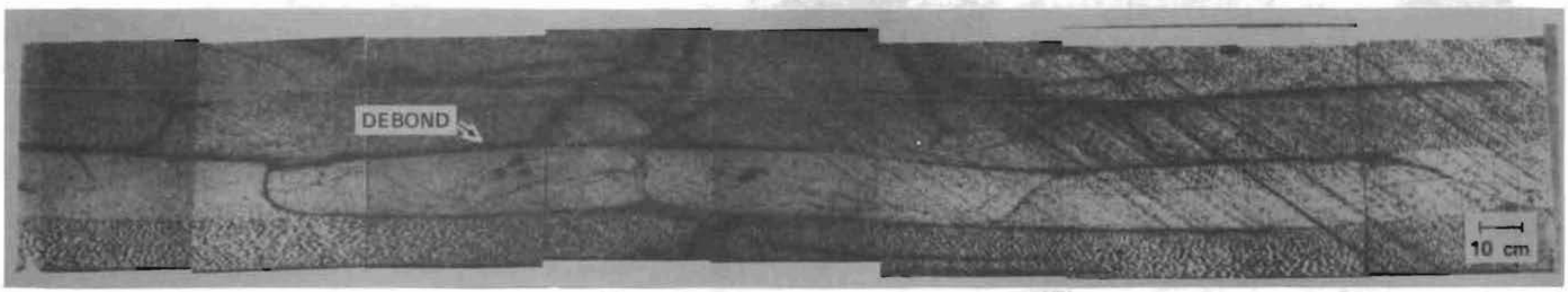
(c). 12K TOW

Figure 11 - Photomicrographs of Flexural Specimen Failure Surfaces:
1 x 1 Braid Pattern, AS-4 Graphite Fiber

(a) 3K Tow



(b) 6K Tow



(c) 12K Tow

Figure 12 - Photomicrographs of Short-Beam Shear Specimen
Failure Surfaces: 1 x 1 Braid Pattern,
AS-4 Graphite Fiber

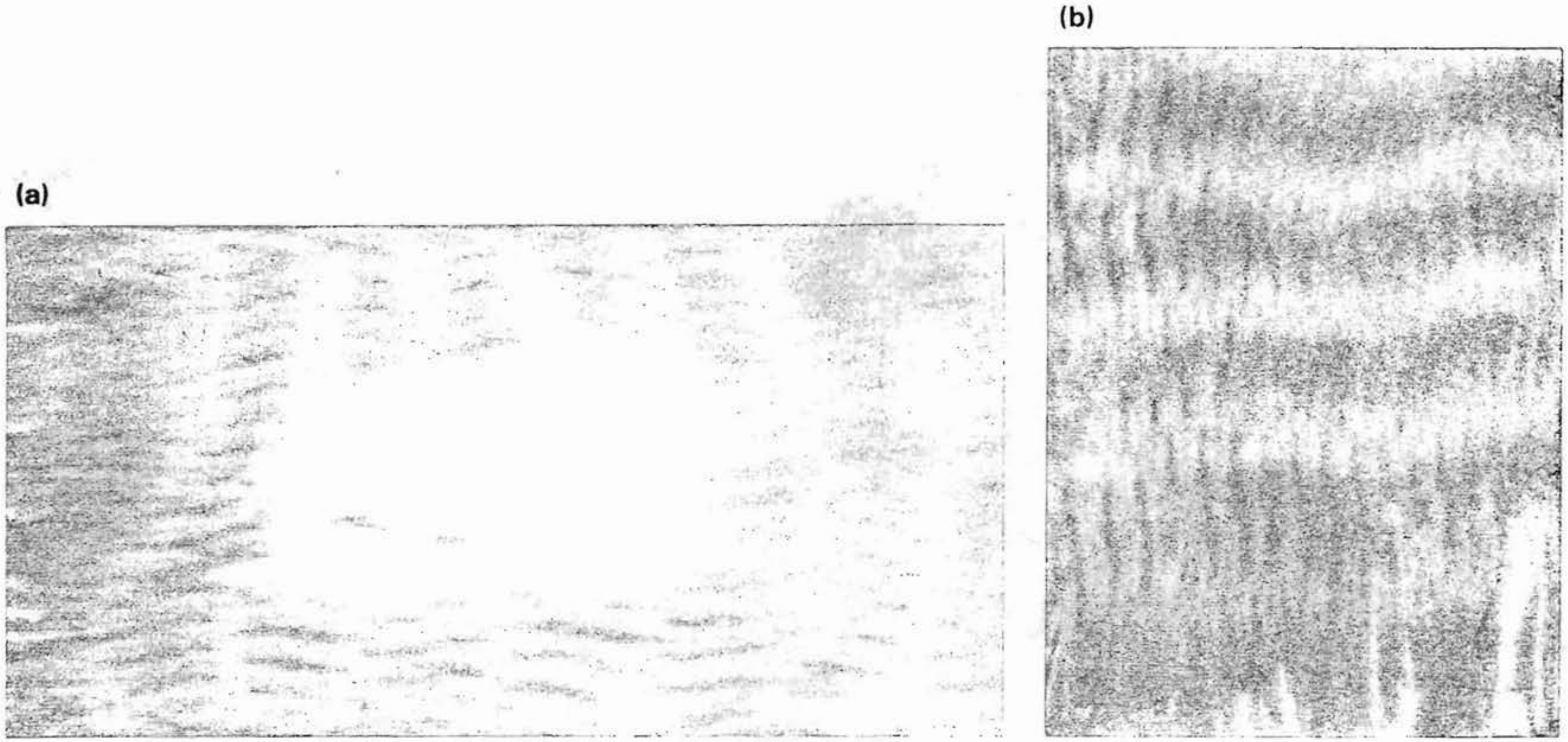


Figure 13 - Ultrasonic C-Scan of 3 x 1 X-D Braided Composites,
(a) Impact Damaged Panel 27 J (20 ft-lb),
(b) Control Panel

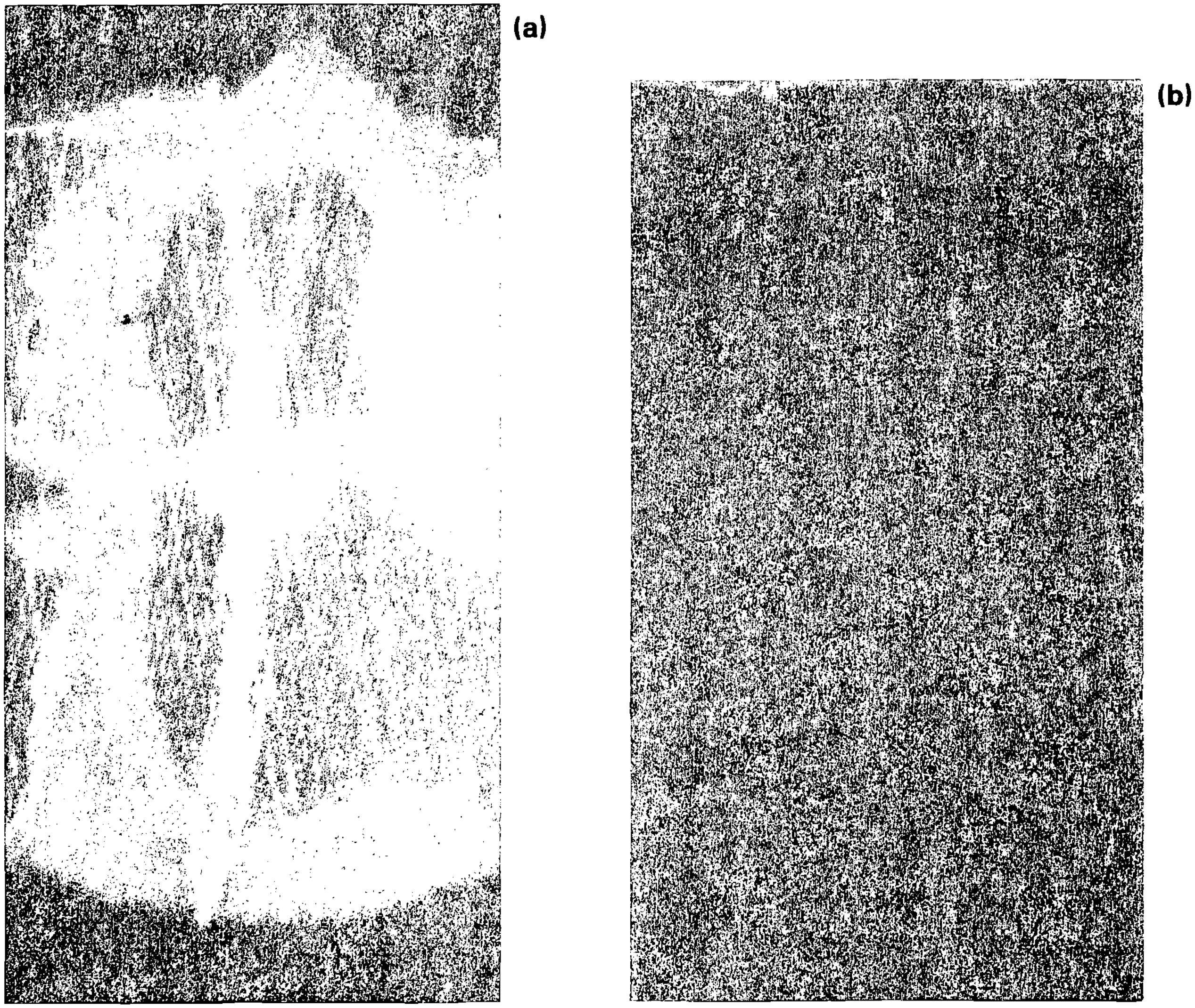


Figure 14 - Ultrasonic C-Scan of $[(10/-10)_6]_S$ Laminates;
(a) Impact Damaged Panel 27 J (20 ft-lb),
(b) Control Panel

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